A Simple and Efficient Computational Approach to Chafed Cable Time-Domain Reflectometry Signature Prediction

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Abstract: A method for the prediction of time-domain signatures of chafed coaxial cables is presented. The method is quasi-static in nature, and is thus efficient enough to be included in inference and inversion routines. Unlike previous models proposed, no restriction on the geometry or size of the chafe is required in the present approach. The model is validated and its speed is illustrated via comparison to simulations from a commercial, three-dimensional electromagnetic simulator.

Keywords: Wire fault, axially slotted coaxial cable, finite difference methods, TDR

1. Introduction

The electromagnetic response of faulted electrical wiring is a topic of increasing importance to a variety of communities. The large majority of previous work in the literature has focused on the radiating properties of faulted wiring and the resultant implications for electromagnetic compatibility. Development of diagnostic and prognostic systems for faulty wiring, in contrast, require understanding of the reflection and transmission properties of faulted wiring.

Although there are a great variety of cable types and faults of potential interest, in this work attention is focused on coaxial cable and "chafe" faults. A chafe is a partial ablation of the outer conductor (and in some cases portions of the core dielectric as well) that typically results from vibration or forced translation of a cable against a structural member or another cable. As a result of the chafe, the return path of a signal on the cable is disturbed. Fortunately, this disturbance is visible to time-domain reflectometry and other methods of interrogation. Thus, the present work aims to find a model for the dynamics of this process so that the response of the chafed cable to various methods of interrogation can be understood, especially as a function of chafe severity. Unlike [1], in which Bethe hole theory (for small chafes) and integral equation techniques (for complete annular interruptions in the shield) were used, the present work makes no use of approximations that restrict the chafe profiles and sizes that can be studied.

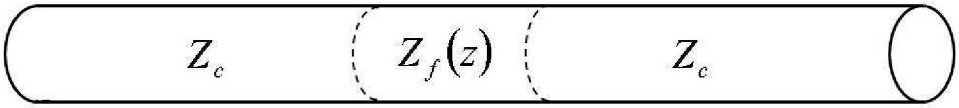

Figure 1: Transmission line representation of the chafed (faulted) coaxial cable. The unfaulted line has a characteristic impedance Z_c, whereas the impedance in the fault is a function of distance $Z_f(z)$ along the line.

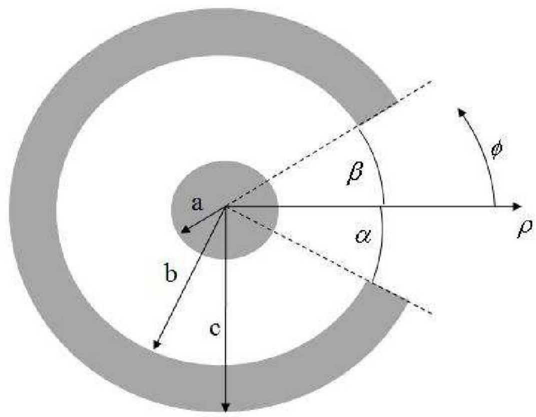

Figure 2: Cross section of geometry under consideration for calculation of fault impedance.

2. Analysis

The proposed analysis treats the cable as a single-moded transmission line and the fault as a single-mode, variably cross-sectioned transmission line. The resulting model of the system is distributed in nature and has a more complex impact on the interrogation signal than a simple differentiation as would be predicted by Bethe hole theory.

Figure 1 depicts an idealized model of the chafed coaxial cable. The cable is assumed to be straight and uniform in the cross-section except in the chafed region. Moreover, for the frequency range of interest (up to 20 GHz) the higher-order mode propagation on the coaxial line is neglected. In general, the high-order modes must be included in a rigorous analysis, however the agreement between the proposed model and simulation results suggests that high-order modes do not play a significant role in the frequency range of interest.

In lieu of a full-blown mode-matching analysis of the chafed cable, it is possible to view each change in cross-section as a simple transmission-line discontinuity. To compute the time-domain response of an inhomogeneous transmission line, the finite-difference time-domain (FDTD) method is used, as elucidated in [2]. What is needed for the analysis, then, is a method of determining the impedance and propagation constant of the chafed coaxial cross-sections.

Figure 2 depicts the cross-section of the faulted region. It is noted that the angles α and β that characterize the severity of the chafe may be allowed to vary as a function of distance in the faulted region. Although TEM propagation is not possible in such a structure (due to the dielectric discontinuity between the core dielectric and surrounding medium), in this work TEM propagation is assumed to expedite the determination of the per-unit-length inductance and capacitance required by the one-dimensional FDTD simulation.

To determine the electrostatic field in the structure represented by Figure 2, the proposed method first solves Poisson's equation

$$-\nabla \cdot \epsilon \nabla \phi = 0 \tag{1}$$

by using a two-dimensional finite-difference algorithm. In this approach, the electrostatic potential is discretized on a grid, the impact of the Poisson operator approximated as a matrix, and the resulting sparse, unsymmetric matrix equation solved via GMRES. Once the electrostatic potential is known, a line integral may be taken at any convenient path that encloses the inner conductor and excludes the outer conductor to evaluate the per-unit-length capacitance.

In the present application, it is the impedance and propagation constant of the chafed coaxial line, not the electrostatic field, which is needed. For TEM wave propagation, it is well-known that the propagation constant and phase velocity are independent of the geometry of the guiding structure,

$$v_p = \frac{1}{\sqrt{\mu_0 \epsilon}} \tag{2}$$

In addition to determining the propagation constant, Eq. 2 renders the inductance per unit length dependent on the capacitance per unit length of the transmission line. Thus, to evaluate the impedance it is sufficient to determine the capacitance, and use the relation

$$Z = \frac{1}{v_p C_l} \tag{3}$$

where C_l is the per unit length capacitance.

In summary, the analysis advocated is as follows. First, divide the faulted portion of the cable into a number of sections. Second, model each section as a TEM transmission line of uniform cross-section, characterized by the angles α and β depicted in Figure 2. Third, determine the propagation constant and impedance of each section using Eq. 2 and Eq. 3 together with a two-dimensional finite-difference analysis of the capacitance of the cross-section. Finally, a one-dimensional FDTD is used to incorporate the actual (finite rise time) interrogation signal and chafed cross-sections, and to evaluate the reflected voltage.

3. Results

The commercial simulator CST Microwave Studio has been used to both validate the proposed solution method and illustrate its computational savings relative to full-wave 3D analysis. As a full-wave, 3D finite integration technique (FIT) simulator, Microwave Studio makes no approximation to the physics of the problem (except for geometrical discretization) and its results can therefore be considered as a ground truth when evaluating approximate methods such as the one advocated in this paper.

Figure 3 depicts the reflected voltage from both the proposed method (blue, solid lines) and CST's Microwave Studio (red, dotted lines). For both cases the parameters $a = 0.25$ mm, $b = 0.8327$ mm, $c = 1$ mm, and $\epsilon_r = 2.0$ characterize the coaxial line, which is assumed to have length 100 mm. A 50 ps rise-time ramp signal was used to interrogate the faults, which are elliptical in shape and have dimensions 2 mm wide and 5 mm long (in the case of the larger signal pair) and 2 mm wide and 1 mm long (in the case of the smaller of the signal pairs). As can be observed,

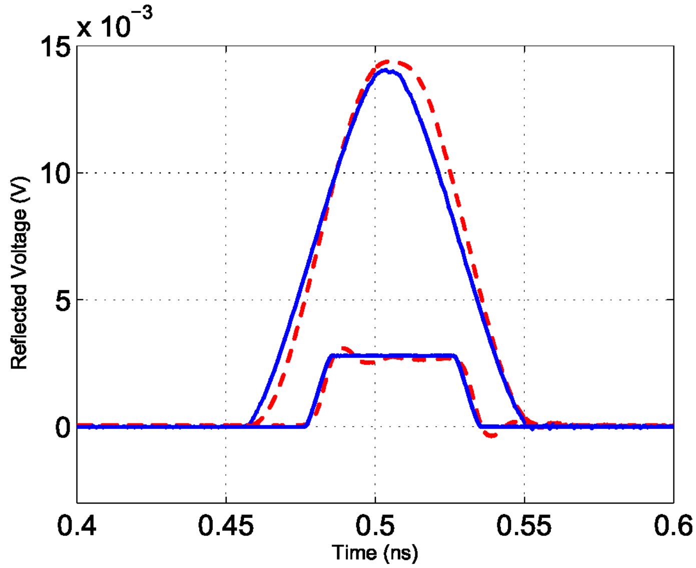

Figure 3: TDR signatures as predicted by the method described herein (blue, solid) and CST Microwave Studio (red, dotted). The larger response comes from an elliptical chafe fault of width 5 mm and length 2 mm, while the smaller response comes from an elliptical chafe fault of width 1 mm and length 2 mm.

excellent agreement between the two methods can be observed, especially in light of the very large dynamic range (approximately 40-50 dB) and very small amplitude of the reflected signal. Accurate prediction of both the TDR signal height, width, and time delay is essential for inversion techniques that aim to reconstruct the geometry of the chafe from the TDR signature. Finally, it is noted that the Microwave Studio simulation (set to 15 lines per wavelength at 20 GHz) required more than 4 hours on a modern PC, while the proposed method required less than one minute.

4. Conclusion

A simple and efficient technique for the prediction of the time-domain refelctometry (TDR) signature from a chafed coaxial cable has been presented. The method relies on a two-dimensional finite-difference discretization of Poisson's equation to determine the equivalent transmission line parameters of the chafed coaxial cable and a one-dimensional finite-difference time-domain (FDTD) discretization of the telegrapher's equations to predict the resulting TDR signature. Despite the approximations made in such a formulation, excellent agreement has been shown relative to a full-wave 3D solution. Finally, the proposed method is efficient enough to be used in inversion techniques that may require thousands of forward model evaluations in an attempt to determine the fault geometry from the TDR signature.

References

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